

ENERGY LEVEL STRUCTURE
IN
HIGHLY IONIZED ATOMS
AND
ASTROPHYSICAL APPLICATIONS

BY
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INTRODUCTION

The improvement of the technical standard during the twentieth century has made possible a comprehensive and detailed registration of electromagnetic radiation - the dominating source of information about the universe. The registration of radiation in space laboratories today has included measurements within large wavelength regions, previously inaccessible because of the strong absorption in the earth's atmosphere. The interpretation of all this information necessitates, among other things, extensive investigations of atomic spectra. The spectra of the cosmically abundant elements are then the most obvious candidates for such studies. However, in a lot of cases the investigation of neighbouring elements in the periodic table is necessary to establish the structure of the "interesting" atom. This implies a great need of data about atomic spectra, several of which are still unexamined.

The present atomic models, based on quantum-mechanical treatment of the atom, provide a good qualitative description of the atomic structure. The quantitative determination of energy levels, however, is in several cases afflicted with relatively large errors due to the approximations used to make the theoretical treatment of the atom possible. An increase of experimental data is then necessary to constitute a basis for further successful progress of the theoretical work.

My scientific work should mainly be assigned to the astrophysical research area, but it has also contributed to the understanding of the atomic structure of elements belonging to the iron group. The thesis consists of the following papers, published in scientific journals.

- I R. Smitt, "The spectrum of three-times-ionized scandium, Sc IV", Physica Scripta 8, 292 (1973)
- II R. Smitt, L.A. Svensson, M. Outred, "An experimental study of $3s^2 3p^k$ and $3s 3p^{k+1}$ in the Cl I, S I, P I, Si I and Al I isoelectronic sequences", Physica Scripta 13, 293 (1976)
- III R. Smitt, "Identification of forbidden coronal lines of Fe X and Ni XII", Solar Physics 51, 113 (1977).

Experimental procedure

All the papers contain investigations of spectra of ionized atoms. The experimental part has in all cases consisted of recording spectra using standard techniques in our laboratory. For light sources I have used either a triggered open spark (for high stages of ionization) or a sliding spark. The discharge voltage has varied between 2 and 60 kV. The spectrograms have been taken in a 5-m grazing-incidence spectrograph (10 - 400 Å), a 3-m normal-incidence spectrograph (250 - 2500 Å) and a 6.4-m Jarrell-Ash spectrograph in a Wadsworth mounting (2000 - 9000 Å). The separation on the spectrogram of different stages of ionization is obtained by varying the inductance in the spark circuit. Fig. 1 shows two exposures of the scandium spectrum around 300 Å. The upper spectrum, which mainly contains spectral lines belonging to Sc IV and Sc V, has been taken with a relatively high circuit inductance. The lower one is recorded with less inductance and contains lines from higher stages of ionization as well.

In the following sections short summaries and discussions of Paper I - III are given.

PAPER I

Paper I, published in 1973, is a comprehensive analysis of three-times-ionized scandium. The analysis of this spectrum was previously highly fragmentary and only eight energy levels were known. Furthermore, all these levels were determined from one single combination, the one to the ground level, $3p^6\ ^1S_0$. The first papers about Sc IV, in which were suggested the identifications of the strong lines $3p^6\ ^1S_0 - 3p^5 4s\ ^1P_1$, 3P_1 , were published in 1937 by Beckman (1) and by Kruger and Phillips (18). These identifications were, however, revised in 1966 by Gabriel et al. (13). The latter authors also added the identification of the transition $3p^6\ ^1S_0 - 3p^5 3d\ ^1P_1$. From my spectrogram, reproduced in Fig. 1, it appears that there are only three strong lines in the actual wavelength region which can be classified as belonging to Sc IV. The

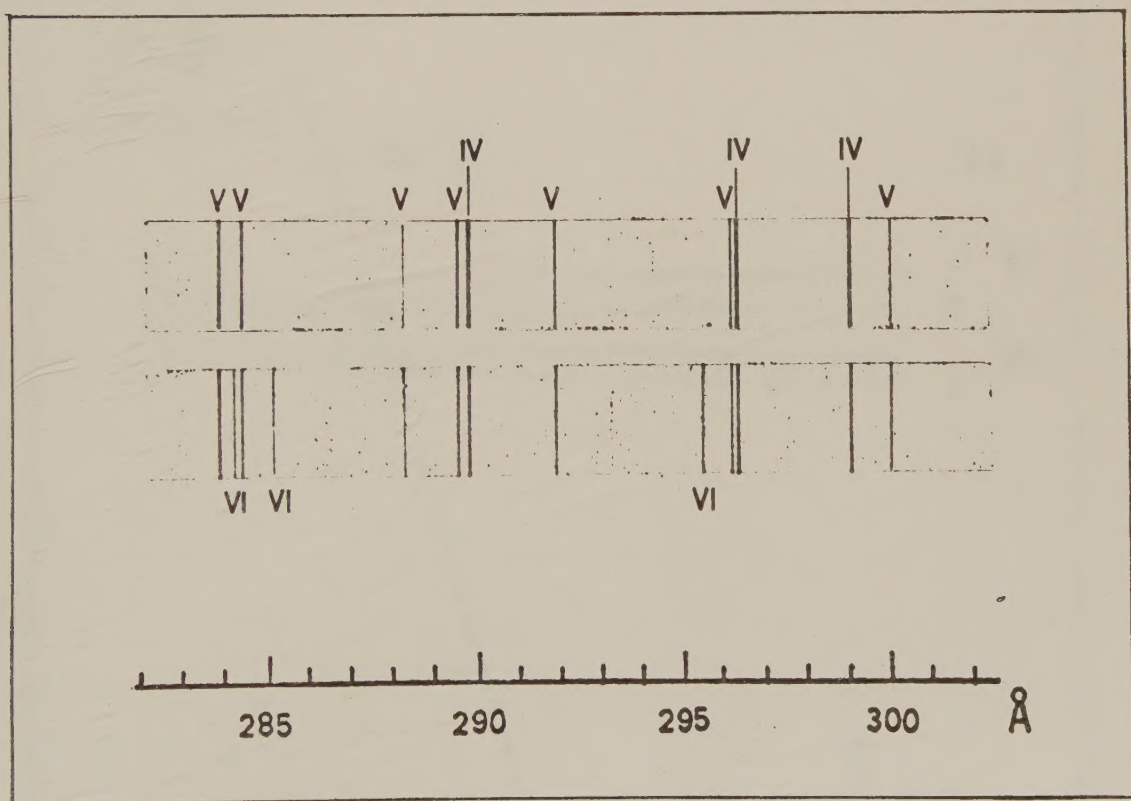


Fig. 1. Illustration of the influence on the relative line intensity caused by the inductance in the spark circuit.

wavelengths of these lines agree with the identifications given by Gabriel et al. In my continued work additional levels that combine with $4s\ ^1P_1$, 3P_1 and $3d\ ^1P_1$ were found and the identifications in Ref. (13) were thus confirmed. The erroneous suggestions by Beckman and by Kruger and Phillips were probably due to the fact that they overlooked the strong interaction in Sc IV between $3d\ ^1P_1$ and the two levels $4s\ ^1P_1$ and 3P_1 . The perturbing effects of this interaction are shown by the isoelectronic comparison in Fig. 2 of the $4s$ configuration in the Ar I sequence. The interaction also causes a strong

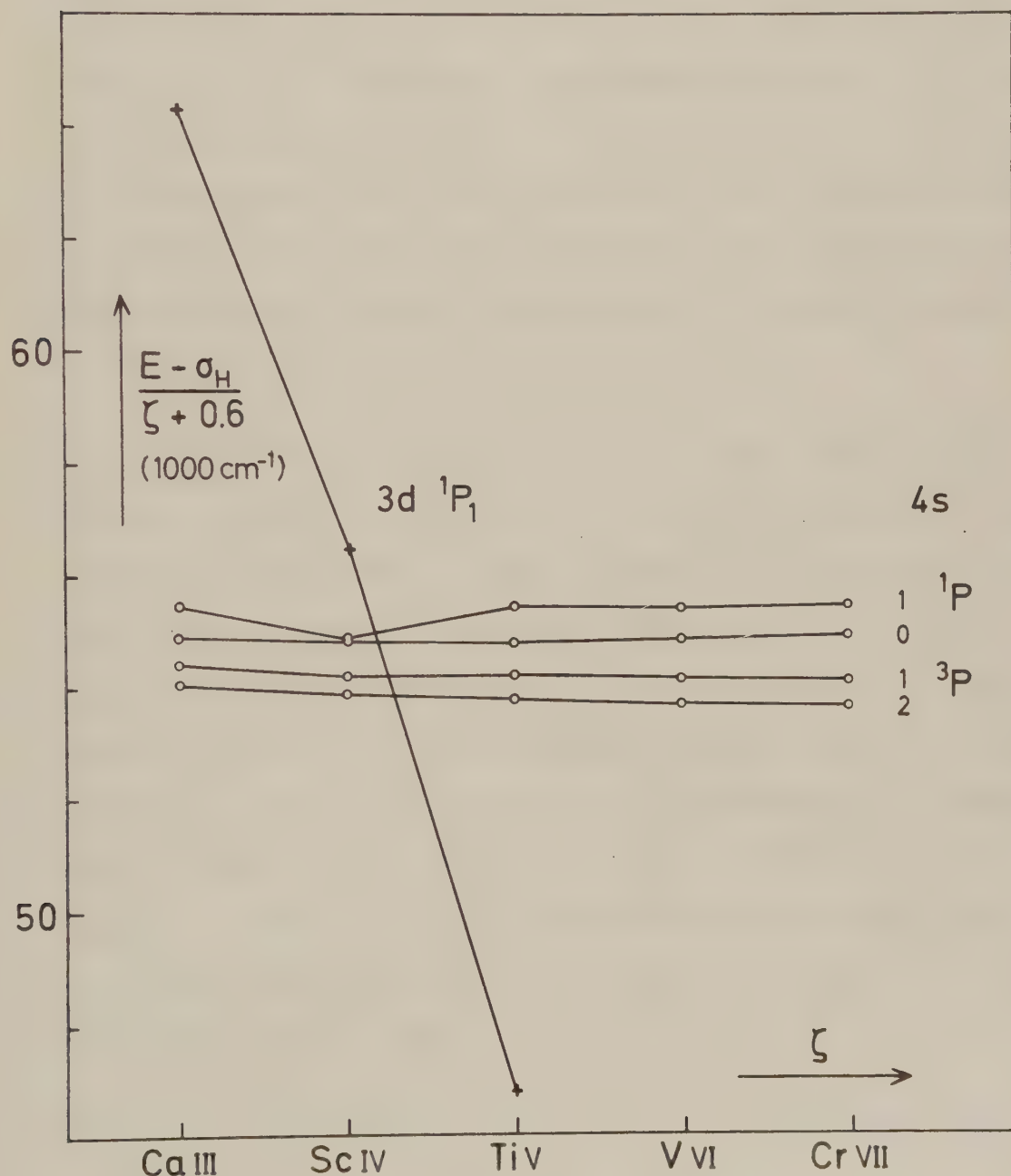


Fig. 2. Isoelectronic comparison of $3p^5 4s$ in the Ar I sequence.

level mixing which allows for "forbidden" transitions between 4s and 4f. Some of them have been observed in this work.

In all about 400 Sc IV lines have been classified, resulting in a determination of more than 100 energy levels. Five of the previous identifications are then confirmed. The wavelengths are based on accurate measurements of several spectrograms. Besides, most of the lines in the wavelength region below 1250 Å have been measured in the second or third order as well. The energy levels are determined by a least-squares-fit to all the observed lines properly weighted. As the analysis also includes measurements of lines in the visual part of the spectrum, it has been possible to provide very accurate calculated wavelengths for the lines between 200 Å and 500 Å. The values, which have an estimated uncertainty of 0.002 Å, have been used in a recent compilation of reference wavelengths by Kaufman and Edlén (17).

By the establishment of configurations with large ℓ -values ($\ell > 3$) an accurate determination of the ionization limit has been possible using the polarization concept. A valence electron in a high ℓ state interacts relatively weakly with the atomic core and the corresponding energy parameters are small. In Sc IV the configurations nh and ni turn out to be excellently described by the use of only three energy integrals, namely E_{av} , ζ_{3p} and $F^2(3p, n\ell)$. The same set of integrals gives a rather good description of the ng configurations as well. However, in order to get a representation within the error limits of the observations the addition of the three small integrals $G^3(3p, ng)$, $G^5(3p, ng)$ and ζ_{ng} is needed.

The Slater integral F^k can be defined by

$$F^k(n\ell, n'\ell') = \iint \frac{r_{<}^k}{r_{>}^{k+1}} R_{n\ell}(r_1)^2 R_{n'\ell'}(r_2)^2 r_1^2 r_2^2 dr_1 dr_2$$

In the case of large values of n' and ℓ' the approximation of $r_{<}$ and $r_{>}$ with r_1 and r_2 , respectively, seems to be rather good. This means that the integral above can be separated into two parts as follows

$$\begin{aligned} F^k(n\ell, n'\ell') &= \int r_1^k R_{n\ell}(r_1)^2 r_1^2 dr_1 \cdot \int r_2^{-(k+1)} R_{n'\ell'}(r_2)^2 r_2^2 dr_2 = \\ &= \langle r_1^k \rangle \cdot \langle r_2^{-(k+1)} \rangle \end{aligned}$$

Thus,

$$F^2(n\ell, n'\ell') = \langle r_1^2 \rangle \cdot \langle r_2^{-3} \rangle$$

Furthermore, as the interaction between the outer electron and the atomic core is very small, the influence on $\langle r_1^2 \rangle$ due to changes of the electronic state ($n'\ell'$) is expected to be negligible. This means that $F^2 \approx \langle r^{-3} \rangle$ with r being the radius of the outer orbital. By inserting the hydrogenic wavefunctions into the expression one gets

$$F^2 = \frac{C}{n^3 \ell(\ell+1/2)(\ell+1)}$$

where C is a constant.

The validity of this formula is easily checked by using the data obtained in Paper I. With the observed value of $F^2(3p, 5g) = 1617 \text{ cm}^{-1}$ the constant C is found to be $1.819 \cdot 10^7 \text{ cm}^{-1}$. The F^2 -values for 6g, 6h, 7h and 7i can then be calculated from the formula. A comparison between observed and calculated values is given in Table I. The differences between them are completely within the uncertainty of the observations.

Table I. Comparison between $F^2(3p, n\ell)$ -values (in cm^{-1}) obtained from the observations in Paper I, (F_{obs}^2), and the corresponding values (F_{calc}^2) given by the formula

$$F^2(3p, n\ell) = \frac{1.819 \cdot 10^7}{n^3 \ell(\ell+1/2)(\ell+1)}$$

n	F_{obs}^2	F_{calc}^2	$F_{\text{obs}}^2/F_{\text{calc}}^2$
5g	1617	(1617) ^a	1.00
6g	938	936	1.00
6h	507	510	0.99
7h	319	321	0.99
7i	191	194	0.98

a) Value used in the determination of the constant $1.819 \cdot 10^7 \text{ cm}^{-1}$.

The ratio between $F^2(n\ell, 5g)$ and $F^2(n\ell, 4f)$ can be checked from observations in several spectra. In his investigation of nitrogen spectra Eriksson (10) determined this ratio using a relatively complicated technique introduced by Bingel (2). He then obtained a ratio of 0.2389 which is in good agreement with his observations. From the considerably simpler formula given above exactly the same ratio is readily obtained.

In addition to the fact that the previous analysis of Sc IV was highly fragmentary and therefore needed an extension, there was at that time a great astrophysical interest for spectra belonging to the Ar I sequence. There were good reasons to believe that an establishment of $3p^5 3d$ in Fe IX and Ni XI would lead to an identification of some of the still unclassified coronal lines. In 1971 Wagner and House (25) had made attempts to determine the actual levels in Fe IX by studying the combinations

3d-4f. Their analysis was, however, incomplete and they were not able to provide any definitive identifications of coronal lines. At our laboratory a comprehensive study of spectra was then started aiming towards the analyses of Fe IX and Ni XI. The investigated spectra were Sc IV (Paper I), Ti V (23), V VI (8) and Cr VII (9). During the work we found that the study of $3s^2 3p^5 3d - 3s 3p^6 3d$ should be the best way of determining the configuration $3p^5 3d$ in Fe IX. By the classification of these transitions in Sc IV a basis for further isoelectronic studies in the Ar I sequence was obtained, and in 1974 Svensson et al. (24) succeeded in identifying about ten coronal lines as Fe IX and Ni XI.

PAPER II

The first observations of emission lines in the solar corona were reported already in the nineteenth century. They were soon followed by more or less probable suggestions as to their identifications. However, the problem was not definitively solved until 1942, when Edlén (4) succeeded in identifying a great number of the coronal lines. Except for one single line they could all be classified as "forbidden" transitions within the ground configurations of highly ionized iron, nickel, calcium and argon. The remaining line was identified as a similar transition in the excited configuration $3s3p$ of Fe XV. Four of the suggested identifications were determined by comparison with laboratory observations of term differences within the ground configurations of Fe X, XI and Ca XII, XIII. The rest of the identifications were based on extrapolations of energy parameters determined from observations in the actual isoelectronic sequences. As the presence of these highly ionized spectra required a much higher corona temperature than previously assumed the publication was received with some scepticism. However, the arguments contained in the careful extrapolation methods used by Edlén gradually convinced the scientific community of the existence of highly ionized elements in the solar corona.

During the following thirty years new measurements of laboratory and coronal spectra were performed. This led Svensson (21) and Edlén (6) to carry out refined isoelectronic investigations of the actual sequences. From the available observations they determined two different sets of the energy integrals $F^2(np, np)$ and ζ_{np} , the Z -dependence of which could be described by means of semi-empirical formulae. The majority of the previous identifications of coronal lines were then confirmed. At the same time Svensson and Edlén were able to make reliable predictions of unobserved transitions in nebulae and the solar corona. Both authors,

however, pointed out that the term values involved needed further improvement.

Paper II contains an investigation of transitions $3s^2 3p^k - 3s 3p^{k+1}$ ($k = 1 - 5$) of the elements K, Ca, Sc, Ti, V, Cr, Mn and Fe. By the investigation the wavelength accuracy has been considerably improved compared to previous measurements (cf Fawcett (11)). Furthermore, about 100 new lines have been classified as being due to these transitions, especially in the spectra of Ti, V, Cr and Mn. The improvement of the ground-configuration levels has made possible a new study of the Z-dependence of the energy integrals. We have then refined the method described above by including the "complete" energy matrices of the ground configurations in the S I, P I and Si I sequences. We have preferred to use the four integrals $F^2(3p, 3p)$, ζ_{3p} , R^1 and $M^0(3p, 3p)$. (The "new" integrals R^1 and M^0 are explained in Paper II). The Z-dependence of these parameters has been described by semi-empirical formulae containing four or five coefficients, the values of which have been adjusted to fit the observations in the sequence.

The formulae are based on the assumption that the energy integrals can be properly described by the use of hydrogen-like wave functions in which is introduced the screening of the nucleus caused by the atomic core electrons. The integral is then expressed as a function of Z by a relation of the form $A(Z - s)^n$, where A is a constant, independent of Z, and n is an integer depending on the actual energy integral. The more complex Z-dependence is contained in the screening "constant" s, the value of which is slightly decreasing throughout the sequence. In order to get formulae useful in practice it is necessary to keep the number of adjustable coefficients at a minimum. Our formulae are not efficient enough to provide a fully acceptable fit to all observed members in beginning of the sequence. Instead of increasing the number of adjustable

coefficients we have preferred to exclude the first three members in each sequence from our calculations. The ground-configuration levels in these spectra are already well determined and we are especially interested in highly ionized spectra. In this way the discrepancies between calculations and observations are essentially within the experimental error limits.

The formula for $F^2(3p,3p)$, $F^2 = A(Z+B+C/(Z-D)) - k \cdot M_{HF}^0$, contains five coefficients to be determined from the observations. As a result we get a value of A , which in the S I and P I sequences agrees with the theoretical value 7898.39 cm^{-1} . As discussed in Paper II the latter is the value of F^2 when hydrogenic wave functions are inserted. In the Si I sequence the observed A -value is somewhat lower. As the observed value of F^2 highly depends on the efficiency in reducing the influence of the electrostatic configuration interaction, we conclude that the interaction parameter R^1 fully accounts for configuration interaction. The last term in the formula is a purely empirical high-order term, which we have introduced to get an acceptable fit to the high members of the sequence. We think that this term is needed to compensate for the exclusion of matrix elements proportional to M^0 , originating from the magnetic orbit-orbit interaction. We have, therefore, chosen a term proportional to M_{HF}^0 (HF: Hartree-Fock). It is possible to include the magnetic orbit-orbit interaction $(-L(L+1) \cdot M^0)$ in the energy matrix without increasing the number of energy parameters. However, as the value of M^0 is determined mainly from the term splitting, this would lead to unwanted effects for high members in the S I sequence, for which M^0 has lost its initial physical meaning. The solid curve in Fig. 3 shows the Z -dependence of M^0 in that sequence and it is obvious that the parameter contains additional interaction effects besides those originally considered by us. This is the reason why we have preferred the use of M_{HF}^0 (dotted curve) in the last term of the F^2 -formulae.

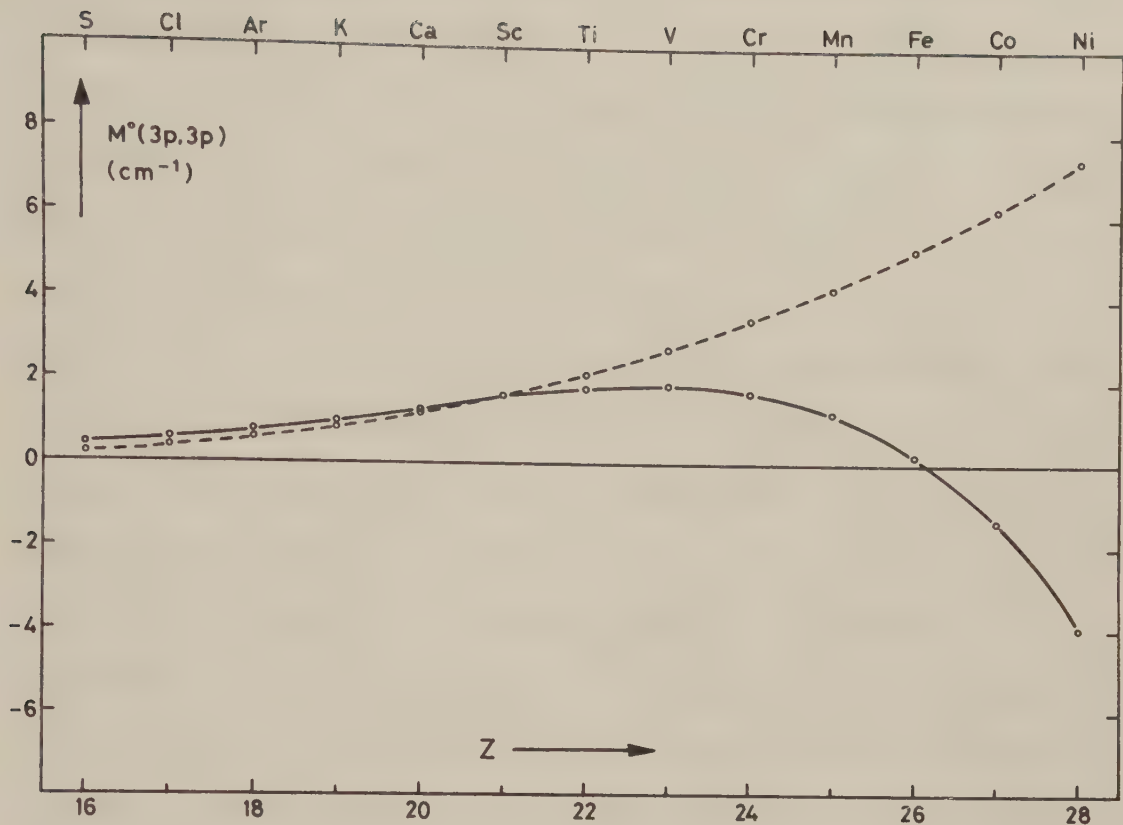


Fig. 3 Comparison between observed (—) and Hartree-Fock (---) values of M^0 in the S I sequence.

We believe, however, that a study of the corresponding sequences with ($n = 2$), that is $2p^k$, would be aided by an introduction of the magnetic orbit-orbit interaction into the energy matrix. In these sequences the value of M^0 is expected to be more significant while the configuration interaction is much simpler. This should then result in a more reliable determination of M^0 . The F^2 -values in the P I sequence are determined mainly by the quartet-doublet separation, which in the spectra studied here is known exclusively in Ar IV, K V, Fe XII and Ni XIV. As the observed separation in Fe XII and Ni XIV also possesses a considerable uncertainty it is impossible to get a sufficiently accurate formula for F^2 by an "ordinary" fit to the observations in the sequence. Alternatively, F^2 can be written $F^2 = A(\zeta + p)$ where $\zeta = Z - N + 1$ and p is a

measure of the penetration of the 3p orbital into the atomic core. If one can get rid of the effects on F^2 from the configuration interaction, the value of A will be the same in all the three sequences. This means that for a fixed value of ζ , the difference ΔF^2 between the F^2 -value in the P I sequence and the average value of the corresponding F^2 -values in the S I and Si I sequences is given by $\Delta F^2 = (p_2 - \frac{1}{2}(p_1 + p_3))$ where p_1 , p_2 and p_3 represent the penetration in the S I, P I and Si I sequences, respectively. If we assume, especially in case of large values of ζ , that the penetration in the P I sequence is approximately the same as the average value of the penetration in the S I and Si I sequences, it should be possible to represent ΔF^2 by hyperbolic function of the type $\Delta F^2 = \frac{a}{\zeta + b} + \epsilon$ where $\epsilon \ll A$. With $a=32$, $b=-2$ and $\epsilon=1$ this function nicely reproduces the ΔF^2 -values determined from Hartree-Fock calculations of F^2 (dotted curve in Fig. 4). According to this fact we have reason to believe that the observed values of ΔF^2 will be represented by a similar function of ζ . The final result is given by the solid curve in Fig. 4. In the case of small ζ the two curves agree remarkably well. The deviation for larger ζ is probably due to the above-mentioned high-order effects contained in the observed values of F^2 .

The electrostatic configuration-interaction parameter R^1 is described by the same kind of formula as F^2 . The choice of a "correct" interaction parameter is essential in order to minimize the contribution of the interaction energy to the value of F^2 . The matrix has been diagonalized with the Trees parameter, α , as interaction parameter, as well. However, this leads to formulae for F^2 with A-values in obvious disagreement with the theoretical value. We therefore consider R^1 to be the better choice for representing the configuration interaction, the net effect

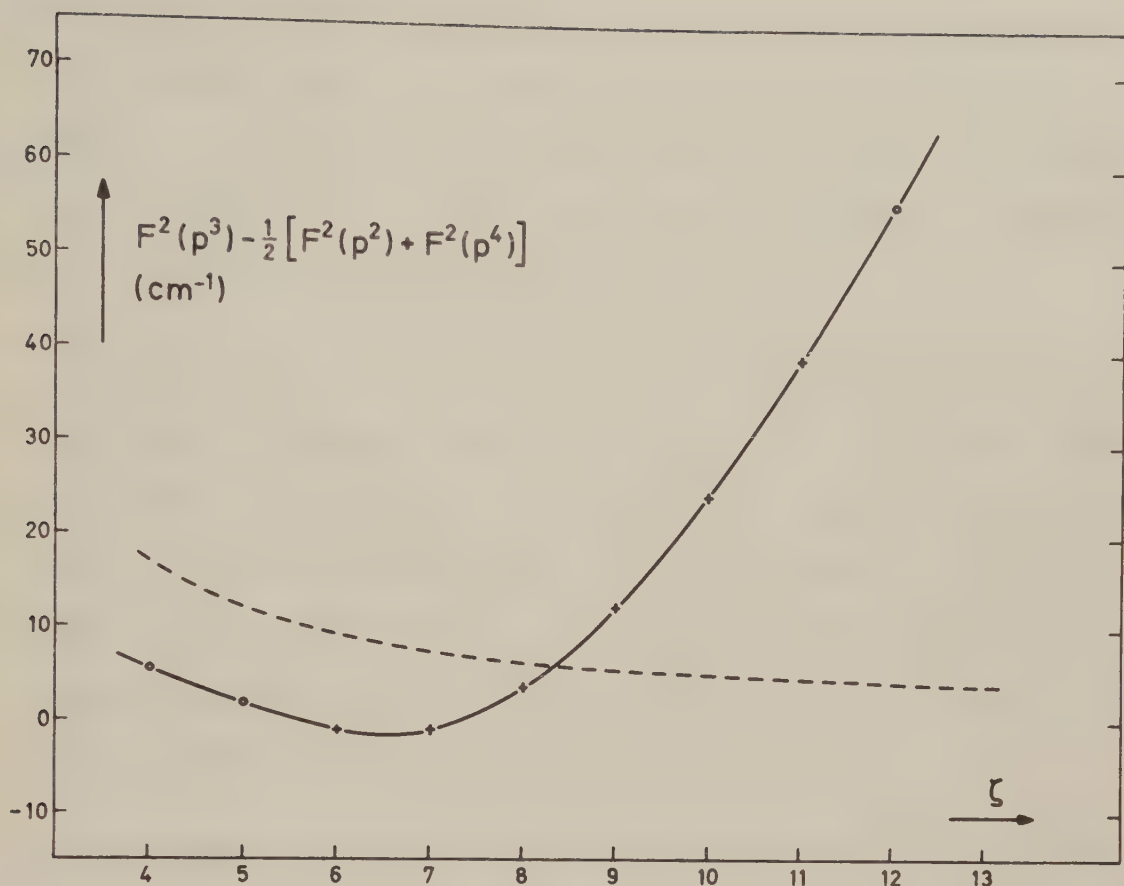


Fig. 4 For ions with the same net charge ζ , the F^2 -values in the $P I$ sequence are compared with the average value of F^2 from the $S I$ and $Si I$ sequences, see text. The dotted curve represents the Hartree-Fock values.

of which is supposed to originate mainly from the interaction between $3s^2 3p^k$ and $3p^{k+2}$.

The spin-orbit integral ζ_{3p} is given by a formula built up by the two equations $\zeta_{3p} = (y + c \cdot (\zeta_{3p})^{3/4})^4$ and $y = A(Z + B + C/y)$. (cf Edlén (6)). The second term in the first equation is included to represent higher terms in the Sommerfeld-Dirac expression of ζ_{np} (Edlén (5, p 168)). In all the sequences we have had to use a value of the constant c about

twice as large as the expected values of $3.20 \cdot 10^{-5}$. This indicates that further effects are contained in this term. The second equation is of the same kind as that used for the electrostatic integrals. However, in the case of ζ_p we have been able to replace the hyperbolic term $C/(Z-D)$ with C/y which then reduces the number of coefficients to be determined from the observations.

The study of ζ_{3p} is extended to the Cl I and Al I sequences, the ground configuration of which consists of a single 2P term. In the Al I sequence we have had to exclude the first three members in our isoelectronic comparison, while the same formula in the Cl I sequence, given by Svensson (22), reproduces the 2P splitting in the beginning of the sequence as well. In all five sequences the value of A comes very close to the theoretical value 0.51856 cm^{-1} .

The spin-spin and spin-other-orbit interaction in $3p^k$, which mainly gives rise to the integral M^0 , was studied by Garstang in 1951 (15). Because of the uncertain measurements available at that time, it was impossible to make a penetrating investigation of the Z -dependence of M^0 . By the improvement of the level accuracy reached in our investigation it has been possible to carry out a quantitative study of these small interaction effects. As expected from the theory, it is shown in the P I and Si I sequences that M^0 can be represented by a formula $M^0 = A(Z - s)^3$. Furthermore, the agreement with the Hartree-Fock values is good, which appears from Fig. 5. In the S I sequence it is impossible to represent M^0 by the formula above (cf Fig. 3). This can possibly be an effect of magnetic configuration interaction, e.g. with $3s3p^43d$. A small influence on M^0 caused by the experimental uncertainty of the measurements is, of course, also possible. Our investigation, however, shows that one has to pay attention to this weak interaction in detailed isoelectronic studies.

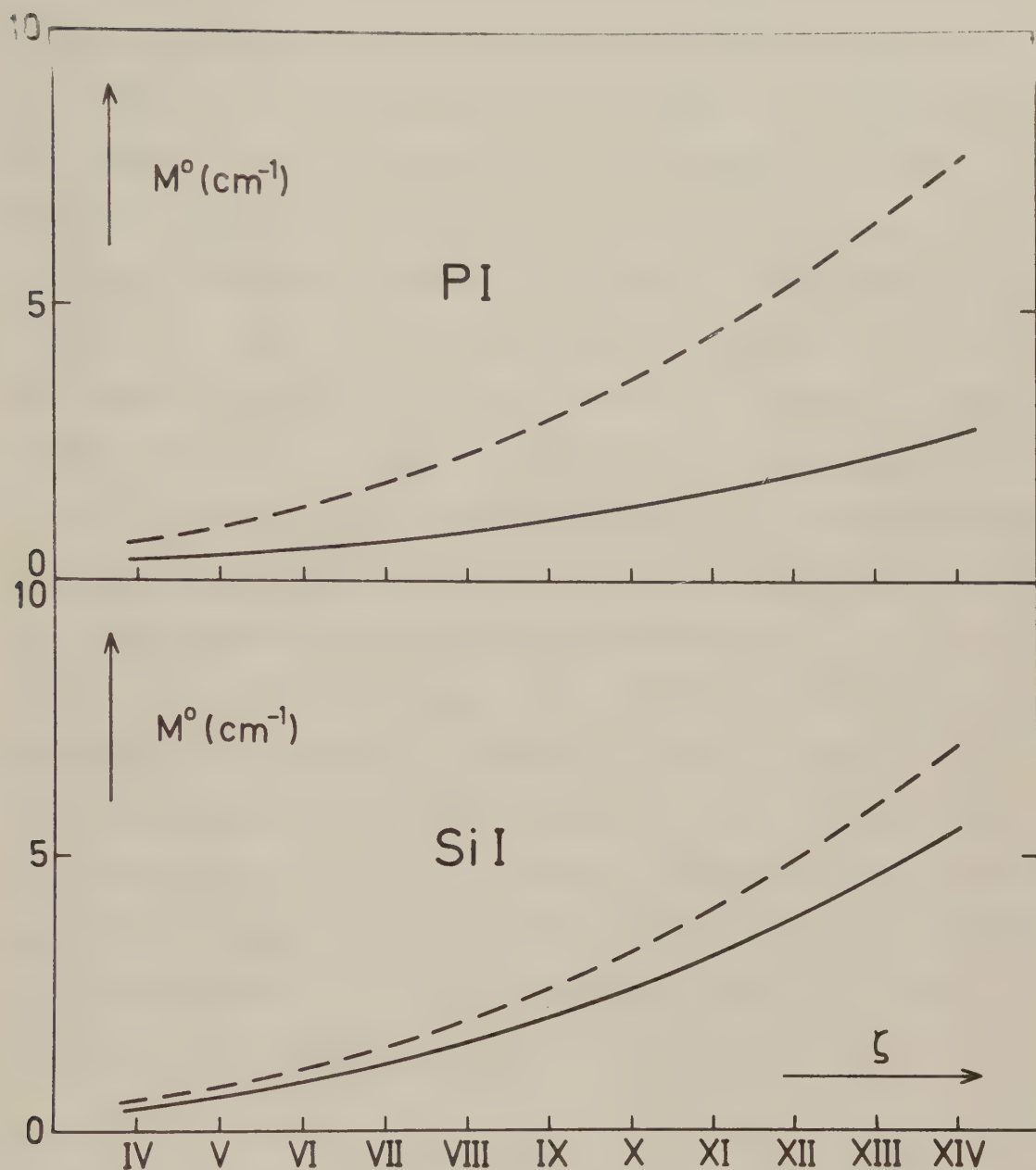


Fig. 5 Comparison between observed (—) and Hartree-Fock (---) values of M^0 in a) the P I sequence
b) the Si I sequence

By means of the level values obtained from the formulae we have been able to predict wavelengths of "forbidden" transitions, which may appear in astrophysical sources. After the publication of our work new measurements in the coronal spectrum have been published by

Sandlin et al. (29) and by Feldman and Doschek (12). Their work includes measurements and identifications of observations from Skylab in the wavelength region between 975 Å and 3000 Å. This has extended the number of coronal lines especially in the region above 2200 Å where no observations previously existed. The wavelength accuracy has also been considerably improved, and is given to a few hundreds of an Ångström. Our predicted values are in Table II compared with the new measurements by Sandlin et al. and by Feldman and Doschek. The wavelengths available at the time of publication of Paper II, have been listed as well. As appears from Table II, most of our predictions are in a remarkably good agreement with the new measurements. The relatively large discrepancies for the Ni XIV transitions $^4S_{3/2} - ^2D_{5/2,3/2}$ at 1867 Å and 2186 Å and $^4S_{3/2} - ^2P_{1/2}$ at 1174 Å may partly be explained by the uncertainty in extrapolating the F^2 -values in the P I sequence. Furthermore, by leaving magnetic configuration interaction out of account (cf M^0 in the S I sequence) the uncertainty of the doublet splitting is somewhat increased. In the case of $^3P_1 - ^1S_0$ in Ni XIII at 1277 Å the deviation is quite acceptable bearing in mind the uncertainty arising in extrapolating the formula of R^1 .

Table II. *Comparison between predictions and observations of coronal lines between 1000 Å and 3000 Å. ^a*

Ion	Combination	λ_{pred}	λ_{obs}^b	λ_{obs}^c	λ_{obs}^d
Ni XIV	$4S_{3/2} - 2P_{1/2}$	1175.34	1174.72		
Fe XIII	$3P_1 - 1S_0$	1216.40	1216.43	1216.46	1216.45(D)
Fe XII	$4S_{3/2} - 2P_{3/2}$	1241.99	1242.00	1242.03	1242.05(BR)
Ni XIII	$3P_1 - 1S_0$	1277.00	1277.23	1277.23	
Mn XII	$3P_1 - 1S_0$	1322.08	1322.2		
Fe XII	$4S_{3/2} - 2P_{1/2}$	1349.53	1349.40	1349.38	1349.47(BR)
Mn XI	$4S_{3/2} - 2P_{3/2}$	1359.53	1359.57	1359.59	
Co XII	$3P_1 - 1S_0$	1368.64	1368.83	1368.84	
Cr XI	$3P_1 - 1S_0$	1439.85	1440.01		
Mn XI	$4S_{3/2} - 2P_{1/2}$	1450.44	1450.49		
Fe XI	$3P_1 - 1S_0$	1466.96	1467.06	1467.08	1467.02(D)
Cr X	$4S_{3/2} - 2P_{3/2}$	1488.93	1489.04	1489.04	
Cr X	$4S_{3/2} - 2P_{1/2}$	1564.06	1564.30	1564.10	
Ni XIV	$4S_{3/2} - 2D_{5/2}$	1867.01	1866.75	1866.75	1866.9(G)
Ni XV	$3P_1 - 1D_2$	2085.8	2085.51	2085.61	2085.7(G)
Ni XIII	$3P_2 - 1D_2$	2125.6	2125.50	2125.50	2126.0(G)
Fe XII	$4S_{3/2} - 2D_{5/2}$	2168.9	2169.08	2169.03	2169.7(G)
Ni XIV	$4S_{3/2} - 2P_{3/2}$	2186.0	2184.26	2184.20	2185.1(G)
Fe XII	$4S_{3/2} - 2D_{3/2}$	2405.6	2405.68	2405.71	
Fe XII	$2D_{3/2} - 2P_{3/2}$	2566.0	2565.93	2565.99	
Fe XIII	$3P_1 - 1D_2$	2578.9	2578.77	2578.77	
Fe XI	$3P_2 - 1D_2$	2648.7	2648.71	2648.73	

a) Air wavelengths above 2000 Å

b) Observed by Sandlin et al. (20)

c) Observed by Feldman and Doschek (12)

d) Observations available at the publication of Paper II: (BR)=Burton and Ridgeley (3), (D)=Doschek (private communication), (G)=Gabriel et al. (14).

PAPER III

As already mentioned briefly, Edlén's identifications of coronal lines in 1942 gradually led to a total revision of the theories about the solar corona. The presence of spectra of highly ionized elements presupposed a plasma with a temperature of more than 10^6 K, an increase from previous models with a factor of about 200. Furthermore, the appearance of "forbidden" lines, originating from magnetic dipole and electric quadrupole transitions, requires an extremely low density because of the small transition probabilities of such transitions. There is today still a great demand of investigations dealing with the corona. The recent observations of the vacuum-ultraviolet part of the spectrum from Skylab have increased the number of observed lines. The origin of some of them is still unknown.

As a conclusion of the work by Svensson et al. (24) in 1974, containing the identification of about 10 coronal lines as "forbidden" transitions within the excited configuration $3s^2 3p^5 3d$ in Fe IX and Ni XI, it was proposed that most of the remaining unidentified lines would belong to the spectra of Fe X, XI and Ni XII, XIII. However, the corresponding configurations in Fe X and XI, $3s^2 3p^4 3d$ and $3s^2 3p^3 3d$ respectively, contain considerably more levels than $3s^2 3p^5 3d$ which makes an experimental investigation more difficult. For instance a determination of the 3d configuration in Fe X includes the classification of at least some 100 lines originating from $3s^2 3p^4 3d - 3s 3p^5 3d$. Besides, the identification of these lines is made difficult because of the great number of lines of lower ionization stages appearing in the actual wavelength region. A successful investigation of these transitions in Fe X must consequently be preceded by a study of elements of lower ionization stages belonging to the same isoelectronic sequence.

The work described in Paper III was started with analyses of Ca IV, Sc V and Ti VI. By including the transitions between $3s^2 3p^4 3d$ and $3s^2 3p^4 4p$ as well, the classification of about 200 lines in each spectrum led to the establishment of the whole configuration $3s^2 3p^4 3d$. From V VII on, the investigation only included the relatively strong quartet-quartet transitions. On the basis of the experimentally determined energy intervals in Fe X, the identification of eleven coronal lines was suggested. By extrapolation of the $^4D_{7/2} - ^4F_{9/2}$ interval another line was identified as Ni XII. In order to make the extrapolation as accurate as possible, I have studied the differences between the observed and the theoretically calculated intervals. The discrepancies thus derived are found to be represented fairly well by a linear function of Z . Before plotting this function the linear part of its Z -dependence can be removed, for instance, by dividing it with $Z + c$ (Fig. 6) or by subtracting a term $c \cdot Z$ (Fig. 7). The high accuracy contained in this method is illustrated in Fig. 7 by the iso-electronic comparison of the interval $^3F_3 - ^3D_3$ in the Ar I sequence. The upper part of Fig. 7 shows the approximate linear Z -dependence of the difference between observed and calculated interval values (σ). By the subtraction of $130 \cdot \zeta$ ($\zeta = Z - 17$) the curve becomes essentially horizontal (lower part of Fig. 7). Hence we conclude that the identification of $^3F_3 - ^3D_3$ in Ni XI, tentatively suggested by Svensson et al. (24) at 3302.8 Å, must be changed to 3338.5 Å. The line at 3302.8 Å is probably originating from the transition $^3P_2 - ^1D_2$ in the ground configuration of Cr IX (cf Table XVI in Paper II). The same extrapolation method has lately been used by Edlén and Smitt (7) in a paper on "forbidden" transitions in iron and nickel. As a result some new identifications have been obtained in Ni XI and Ni XII. Moreover, their study of relative line intensities provides a confirmation of all the suggested Fe X identifications except for $^4F_{7/2} - (^1D)^2F_{7/2}$ at 1582 Å. According

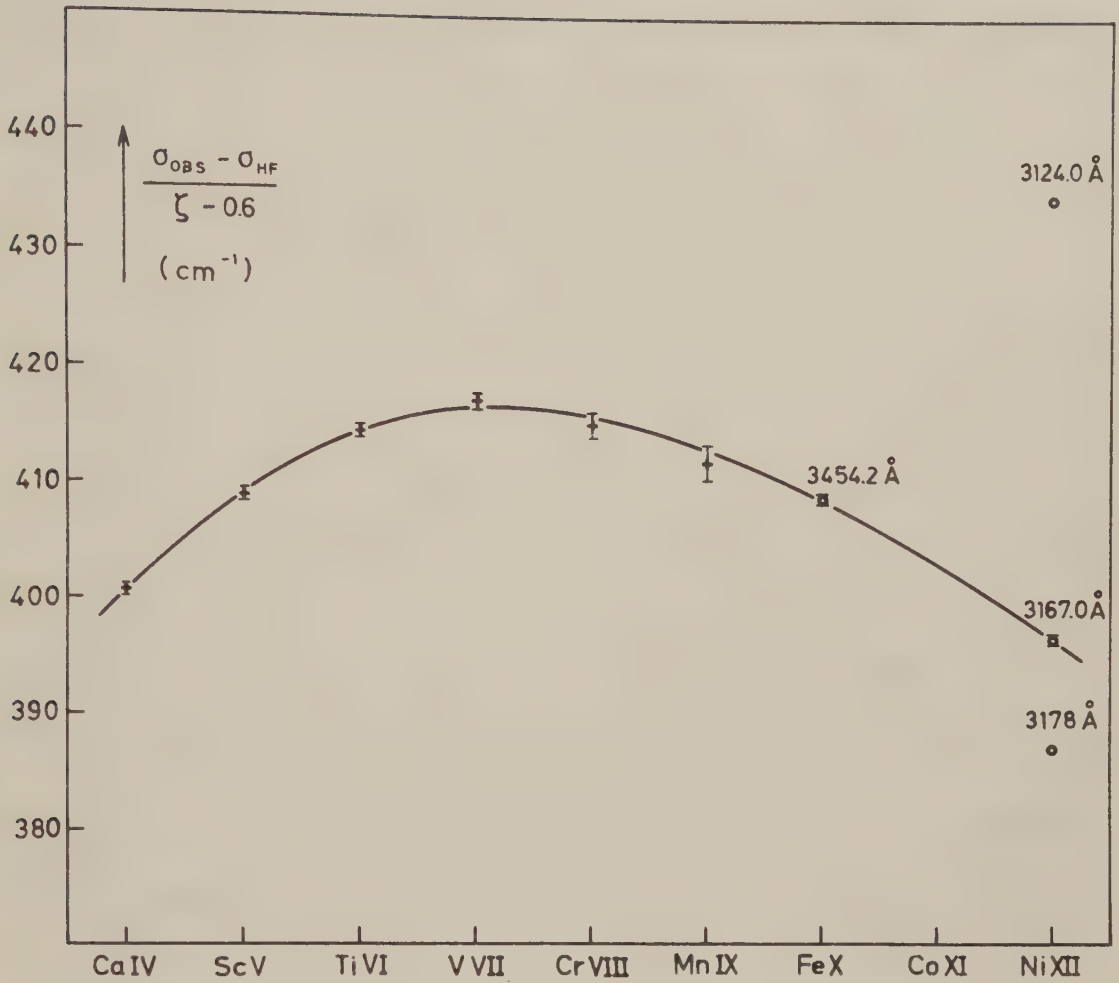


Fig. 6 Isoelectronic comparison of the interval $3p^4 3d^4 D_{7/2} - ^4F_{9/2}$ in the Cl I sequence (see Fig. 1 in Paper III).

to available theoretical transition probabilities (calculated by Cowan), the intensity of this line should be vanishingly small. The perfect agreement with the predicted wavelength, however, speaks for the suggested identification which is furthermore supported by the temperature classification as given by Feldman and Doschek (12) and by Jordan (16).

Paper III is an important step towards increased knowledge about the solar corona. Except for the fact that the number of unidentified lines

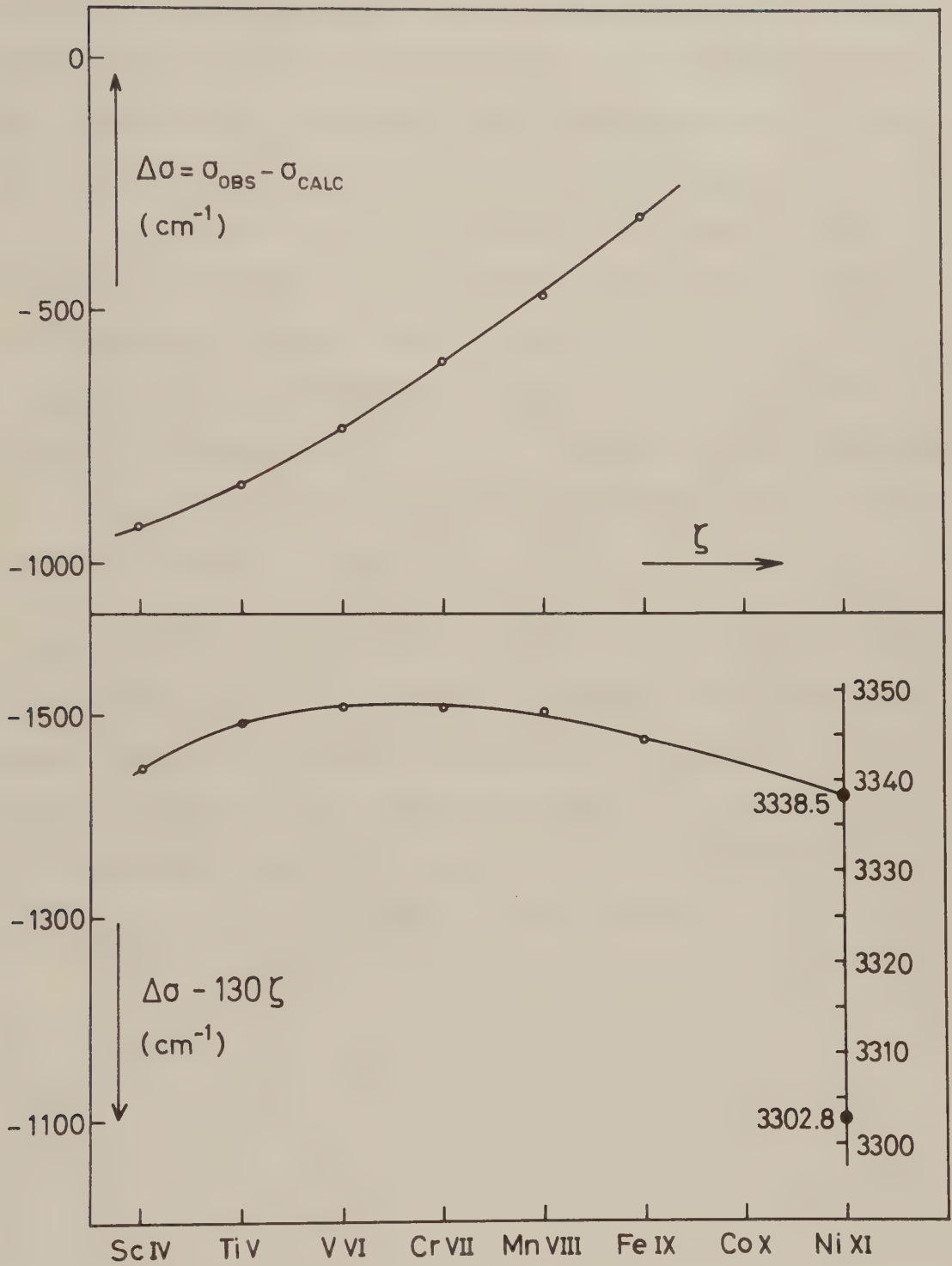


Fig. 7 Isoelectronic comparison of the interval $3p^5 3d {}^3F_3 - {}^3D_3$ in the Ar I sequence by studying the differences between observed and calculated values.

has been greatly reduced, the classification of a relatively large number of lines belonging to the same ion improves the possibility of checking interesting parameters in the proposed theoretical model such as density and temperature. Of the remaining unidentified lines the majority will certainly turn out to be transitions within $3s^2 3p^3 3d$ in Fe XI. As in the case of Fe X, Mason and Nussbaumer (19) have calculated the emissivity ratios for these lines. As a consequence they suggest the identification of $\lambda 4566.2$ as $(^2D) \ ^3F_4 - ^3G_5$ of Fe XI. The only remaining unidentified line above 3000 Å, namely $\lambda 3488.5$, will perhaps be explained as $(^2D) \ ^3F_4 - ^1G_4$. However, a careful investigation of Fe XI in the coronal spectrum must be carried out with a technique similar to that used in Paper III.

Further studies of the 3d configurations in Fe X and XI are also highly interesting because the 3p - 3d resonance lines are expected to appear in the solar spectrum at about 200 Å. A great deal of the experimental data necessary for these investigations is already available on the spectrograms used in the present work, and I hope to be able to study these fascinating problems in a near future.

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